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Validity of segmental multiple-frequency bioelectrical impedance analysis to estimate body composition of adults across a range of body mass indexes

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Abstract

Objective: We compared body composition estimates using an eight-electrode, segmental, multiple-frequency bioelectrical impedance analysis (segmental MF-BIA) and dual x-ray absorptiometry (DXA) in a group of healthy adults with a range of body mass indexes (BMIs).

Methods: Percentage of body fat (%BF), fat-free mass, and fat mass assessed by DXA and segmental MF-BIA in 132 healthy adults were classified by normal (N; 18.5–24.9 kg/m^2), overweight (OW; 25–29.9 kg/m^2), and obese (OB; 30–39.9 kg/m^2) BMI.

Results: Compared with DXA, segmental MF-BIA overestimated %BF in the OB BMI group (3.4%; $P < 0.0001$). MF-BIA overestimated %BF among men (0.75%; $P < 0.006$) and women (0.87%; $P < 0.006$) and underestimated it in the N BMI group (−1.56%; $P < 0.0001$); %BF was not different between methods in the OW BMI group. Error in %BF determined by segmental MF-BIA and DXA increased as %BF increased ($r = 0.42$, $P < 0.0001$). Waist circumference was the only significant predictor of systematic error in %BF between MF-BIA and DXA ($r = 0.60$, $P < 0.0001$).

Conclusion: Eight-electrode, segmental MF-BIA is a valid method to estimate %BF in adults with BMI classified as N and OW, but not as OB. Estimation of trunk resistance with current segmental MF-BIA devices may explain the underestimation of %BF in the adults with OB BMI. Further examination of the effect of waist circumference and body fat distribution on the accuracy of BIA measurements is warranted.

Keywords: Bioelectrical impedance analysis; Body composition; Body mass index; Dual x-ray absorptiometry

Introduction

Approximately 60% of Americans are overweight and obese [1]1. This burgeoning public health concern has prompted numerous interventions to facilitate healthy weight management [2]. Body composition assessment is an important outcome measurement in weight management interventions because of the importance to maintain muscle and bone and reduce fat. Thus, techniques that provide valid assessments among individuals of varying levels of body fatness are critical to evaluate intervention outcomes.

Bioelectrical impedance analysis (BIA) is a practical and non-invasive method to assess human body composition. Unlike dual energy x-ray absorptiometry (DXA) and underwater weighing, BIA is practical and does not have weight and height restrictions limiting its use with certain populations. Whole-body and segmental BIA approaches have been developed for assessment of human body composition. Initial applications of BIA at 50 kHz used whole-body measurements of resistance, derived by using surface electrodes placed on a hand and a foot, and the height of the

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subject in sample-specific regression models [3]. Single-frequency (SF) BIA was based on the postulate that the human body was a single cylinder with constant resistivity [4]. A limitation of whole-body SF-BIA is that the trunk contributes little (~10%) to whole-body resistance but contains a large content (~50%) of conductor volume [5], which is particularly important in overweight and obese individuals [6,7].

Segmental BIA may overcome this problem in obese individuals. This technique recognizes that the human body is complex in shape, represented not by one uniform but five heterogenous cylinders (e.g., arms, trunk, and legs) with different resistivities, over which resistances are measured separately [8]. Knowledge of segmental body composition is important to identify health-related risk factors, because regional fat distribution (e.g., trunk and abdomen) is a predictor of risk of diabetes and heart disease [9,10].

Some findings have suggested that SF-BIA may not accurately assess body composition with increasing adiposity [11,12] because the altered electrical properties of tissues [6] require frequencies higher than 50 kHz to penetrate all tissues. Multiple-frequency BIA (MF-BIA), which measures impedance at a range of multiple or a fixed set of frequencies, is appealing because of its potential to assess fluid distribution [13,14].

Segmental MF-BIA has been used to estimate body composition in adults [15,16]. However, the validity of this device to estimate body composition of individuals with varying levels of adiposity is not well established. This study compared estimates of body composition determined by using segmental MF-BIA and DXA in healthy adults stratified into groups based on body mass index (BMI). We hypothesized that percentage of body fat (%BF), fat mass (FM), and fat-free mass (FFM) would not be significantly different between segmental MF-BIA and DXA across BMI groups.

Materials and methods

Subjects

One hundred thirty-two healthy adults were recruited for this cross-sectional study. The goal was to study 44 subjects in each of three BMI groups (normal [N], 18.5–24.9 kg/m^2; overweight [OW], 25–29.9 kg/m^2; and obese [OB], 30–39.9 kg/m^2). Inclusion criteria were age ≥18 y, BMI ≥18.5 and <40 kg/m^2, absence of self-reported chronic disease, no use of medication that could influence body water balance, absence of pregnancy or lactation, no metal inserts or pacemaker, and an ability to stand erect independently without support.

Protocol

Standing height (±2 mm) and weight (±0.1 kg) were measured at an information meeting to group subjects into the appropriate BMI classification. Subjects provided written informed consent and scheduled their testing appointment after receiving oral and written descriptions of the study protocol. Subjects were instructed to abstain from caffeine, physical activity, showering/bathing/sauna within 4 h of testing; abstain from food within 2 h of testing; refrain from alcohol 24 h before testing; not donate plasma or blood 2 d before testing; and avoid wearing undergarments with metal. Women were instructed to schedule their appointment during the 6th–10th days of their menstrual cycle to minimize the effects of fluid retention. The study was approved by the institutional review board at the University of North Dakota.

Dual x-ray absorptiometry.

Percentage of body fat was estimated from FM and FFM measured by using DXA (QDR DELPHI-W DXA fan beam mode; software version 11.2.1:7; Hologic, Bedford, MA, USA). Daily calibration was performed by using a spine phantom daily and when the DXA was idle more than 2 h between tests. The within- and between-day variabilities for bone mineral density were 0.17% and 0.30%, respectively. The variability (coefficient of variation) for total body fat from DXA ranges from 1% to 3% [17,18]. Subjects wore hospital-style scrubs without shoes or socks during the procedure. Scrubs were selected because they were uniform, lightweight, and without metal, and preliminary data showed they had no effect on the validity of body composition results.

Eight-electrode, segmental BIA.

Percentage of body fat was estimated using a segmental MF-BIA instrument (InBody 320, Biospace Co., Ltd., Seoul, Korea) that operated at frequencies of 5, 50, and 250 kHz, which were pre-set by the manufacturer to assess extracellular fluid and total body water and introduced into the body in ascending order of frequency. This device uses contact electrodes, located in the handgrips and the footpads, to measure resistance, does not require standardization of a subject's posture before testing, and is quick compared with standard four-electrode devices that require time to normalize body fluid distribution before testing [19]. Subjects stood with the ball and heel of each foot on two metallic electrodes on the floor scale and held handrails with metallic grip electrodes in contact with the palm and thumb [19,20]; arms were fully extended and abducted approximately 20 degrees laterally. For each of the programmed frequencies, an alternating current of 250 μA was applied between the electrodes at the right palm and ball of the right foot. The voltage decrease between the electrodes at the right and left thumbs was divided by the applied current to obtain the resistance of the right arm. The same procedure was performed with voltage decrease recorded between the right and left heels to obtain right leg resistance, and between the electrodes on the left thumb and left heel to obtain trunk resistance. The current was then applied between the left thumb and left foot and the value of the recorded

voltage decrease between the right and left thumbs was used to calculate the resistance of the left arm. The voltage decrease between the right and left heels was used to calculate the resistance of the left leg.

If an error reading occurred due to dry skin, subjects were instructed to wipe their palms and foot soles with an electrolyte cloth provided by the manufacturer and the test was repeated. Internal calibration of the device was measured by using a resistance-capacitance model assembled with precision resistors and capacitors at the beginning of each testing week; the variability between days was 0–0.4% across all frequencies. The within-day variability from three daily resistance measurements of four individuals over 5 consecutive days was 0–2.4% across all frequencies and sites; between-day precision was 1.7–3.9%. Variabilities from previous research with eight-electrode MF-BIA were <2.0% within days and <3.0% between days [16,20,21].

Although this segmental MF-BIA device measures the resistance of each body segment described above, it does not provide estimates of regional or segmental body composition; only whole-body estimates are given. This instrument measures segmental resistance and not impedance. Resistance measurements can be summed, whereas impedance values, which are vector quantities, cannot be added over adjoining segments to constitute a larger portion of the body. Whole-body resistance (R_{SumX}) was calculated by adding the segmental resistances at each (X) frequency: $R_{SumX} = R_{RA} + R_{LA} + R_T + R_{RL} + R_{LL}$. Segmental and whole-body resistive indexes were calculated as standing height $(Ht)2/R_X$ and $Ht2/R_{sumX}$, respectively. Proprietary equations from the manufacturer were used to estimate whole-body composition variables.

Anthropometry.

Because discrepancies in total and trunk body fatnesses have been observed between BIA and DXA, we examined the relation between anteroposterior (AP) body thickness, waist circumference, and systematic error between DXA and MF-BIA [12]. Excessive AP thickness affects the transmission and absorption of x-rays from DXA particularly in individuals with an AP thickness greater than 25 cm [22]. Supine AP thickness was measured from the surface of the DXA table to the highest body point with anthropometry calipers (Harpender Anthropometer; Holtain Limited Company, Crosswell, Crymych, United Kingdom) to the nearest centimeter. Supine waist circumference was measured at the umbilicus to the nearest centimeter. If the difference in repeat AP thickness and waist circumference measurements was greater than 1 cm, a third measurement was taken and the average of the two closest measurements was used.

Data analysis

Power analysis indicated that a sample of 132 subjects, 44 in each BMI group, would provide 90% power to detect a mean difference of 2% body fat between methods within each BMI range. A within-subject standard deviation of 2.5% body fat and an α value equal to 0.05 were used.

A 2 × 3 analysis of variance using the Proc GLM procedure [17] was used to determine the effect of group (gender and BMI) on body composition variables estimated with DXA and segmental MF-BIA. Tukey-Kramer contrasts were used for post hoc pairwise comparisons of means when appropriate. Differences in body composition estimated by the two methods were determined by testing whether the difference within a gender and BMI group was significantly different from zero. Stepwise regression analysis was used to determine the best predictors of the error in %BF between DXA and segmental MF-BIA. Potential predictors included waist circumference, AP thickness, %BF, and FM as measured by DXA. For the stepwise regression, the significance level for a variable to be added to the model was set at 0.1 and the significance level for a variable to remain in the model was set to 0.15. For all other statistical tests, the significance level was $P < 0.05$. Data are reported as mean ± pooled standard error, unless otherwise indicated.

Results

Table 1 presents the physical characteristics of the subjects listed by gender and BMI groups. DXA FFM was greater and FM and %BF were lower in men than in women (all Ps < 0.0001; Table 2). %BF, FM, and FFM from DXA increased across BMI groups (all Ps ≤ 0.01). Compared with DXA, segmental MF-BIA overestimated %BF in women and men ($P < 0.006$) and the OB BMI group ($P < 0.0001$) and underestimated %BF in the N BMI group ($P < 0.04$). A similar trend for FM was observed in women, men, and the OB BMI group ($P < 0.001$), with an overestimation by MF-BIA also in the OW BMI group ($P < 0.0001$). FFM estimated by DXA and MF-BIA was not different for women but was overestimated by MF-BIA in men ($P < 0.04$) and in the N and OW BMI groups ($P < 0.0001$). In contrast, MF-BIA underestimated FFM in OB subjects ($P < 0.0001$). Differences in %BF, FM, and FFM between DXA and MF-BIA were not different between men and women but were different across BMI groups ($P < 0.05$). The sex-by-BMI interaction was not significant.

Assessment of bias in the aggregate data showed that the error of estimating %BF with segmental MF-BIA compared with DXA increased as %BF increased ($r = 0.424$, $P < 0.0001$; Fig. 1A), and limits of agreement (mean ± 2 SD) were −5.7% to 7.2% body fat. There were no statistically significant trends in error identified when the groups were examined individually (Fig. 1B–D). Modest error was observed between methods for the N group (mean difference −1.56%; Fig. 1B) and OW group (mean difference 0.58%; Fig. 1C), and the bias did not change significantly over the range of %BF values within each group. A greater amount

Table 1
Descriptive characteristics and body composition variables by gender and BMI*

Variable	Women (n = 69)	Men (n = 63)	Normal BMI (n = 46)	Overweight BMI (n = 44)	Obese BMI (n = 42)
Age (y)	43.6 ± 1.6 (19–72)	41.4 ± 1.7 (19–81)	35.5 ± 2.0^{a} (19–63)	45.0 ± 2.1^{b} (20–81)	46.9 ± 2.0^{b} (19–72)
Height (cm)	162.5 ± 0.7^{a} (151.3–180.1)	179.7 ± 0.7^{b} (165.4–189.7)	173.0 ± 0.8^{a} (156.4–188.9)	170.7 ± 0.9^{ab} (151.3–186.9)	169.6 ± 0.9^{b} (153–189.7)
Weight (kg)	73.3 ± 0.9^{a} (49.6–98.7)	90.0 ± 0.9^{b} (52.6–131)	68.1 ± 1.1^{a} (49.6–82.1)	80.0 ± 1.1^{b} (63.1–101.6)	97.1 ± 1.1^{c} (72–131.5)
BMI (kg/m^2)	27.9 ± 0.2 (18.7–38.1)	27.9 ± 0.2 (19.2–39.3)	22.7 ± 0.3^{a} (18.7–24.9)	27.3 ± 0.3^{b} (25.1–29.8)	33.7 ± 0.3^{c} (30.1–39.3)
AP thickness (cm)	166.2 ± 2.0^{a} (109–236)	183.5 ± 2.0^{b} (131–245)	149.7 ± 2.4^{a} (109–194)	171.6 ± 2.5^{b} (138–205)	203.2 ± 2.5^{c} (166–245)
Waist circumference (cm)	87.9 ± 0.8^{a} (67–122.6)	96.6 ± 0.9^{b} (72–126.5)	79.5 ± 1.0^{a} (67–94.5)	90.4 ± 1.1^{b} (71.6–106.1)	106.8 ± 1.1^{c} (87.7–126.5)

AP, anteroposterior; BMI, body mass index
* All values reported as mean ± SE (range). Means not sharing a common superscript letter are significantly different between genders or between BMI groups ($P \leq 0.02$).

of bias was present in the OB BMI group (mean difference 3.4%), although the error was not significantly affected by the range of %BF (Fig. 1D). Limits of agreement were −6.7% to 3.6% for the N group, −3.8% to 5.0% for the OW group, and −2.0% to 8.8% for the OB group (Fig. 1B–D).

Stepwise regression analysis showed that waist circumference was the only significant predictor (r = 0.60, $P <$ 0.0001) of the error between segmental MF-BIA and DXA, explaining 36% of the variance in the overall sample (Fig. 2). When each BMI group was examined separately, waist circumference was not a significant predictor of the error in any BMI group.

Discussion

The search for a practical and valid method to assess human body composition continues to focus on BIA techniques. The four-electrode, whole-body SF-BIA approach has poor precision of estimates for an individual because of reliance on sample-specific regression models [18]. MF-BIA shows relative agreement (e.g., significant correlation coefficients) with reference fluid volumes and body composition estimates but significantly overestimates these variables compared with reference methods [23,24]. Segmental BIA is a novel approach that may overcome the limitations of these whole-body techniques by estimating impedance of the limbs and trunk [8].

Attempts to assess the validity of segmental BIA to estimate various body composition parameters have only focused on comparisons in groups without rigorous examination within subgroups defined by ranges in body size or composition [11,15,25]. The present study addressed this limitation by using a sample selected to provide normal, overweight, and obese adults. The key finding was that segmental MF-BIA significantly underestimated %BF in the N group (−1.56%), and overestimated it in the OW (0.58%) and OB (3.4%) groups. This finding supports the hypothesis that body composition estimates are less accurate with BIA at increasing levels of adiposity [6].

There is a paucity of reports examining the validity of segmental MF-BIA to estimate %BF. Demura et al. [11] reported that segmental MF-BIA yielded similar estimates of %BF as DXA (12.5% versus 11.1% and 19.5% versus 20.6% in men and women, respectively) in 45 relatively lean (16% body fat) college students. Inconsistent findings between these studies may be explained by the heterogeneity in body fatness in the present compared with the previous study [11].

Validation of segmental SF-BIA has yielded mixed results. Pietrobelli et al. [25] reported no significant difference in estimates of %BF in 40 subjects, 6–64 y of age, although segmental BIA at 50 kHz overestimated body fatness by 2.6% compared with DXA. Similarly, 50-kHz segmental BIA overestimated body fatness 3.2% in normal-weight and 5% in overweight adults [11]. %BF also was overestimated (2.6%) in lean college students assessed with SF-BIA [15].

Table 2
Comparison of percentage of body fat, fat mass, and fat-free mass from DXA and eight-electrode segmental MF-BIA by gender and BMI*

Variable/method	Women (n = 69)	Men (n = 63)	Normal BMI (n = 46)	Overweight BMI (n = 44)	Obese BMI (n = 42)
Body fat (%)					
DXA	35.60 ± 0.58[a]	22.62 ± 0.60[b]	22.39 ± 0.71[a]	29.63 ± 0.72[b]	35.32 ± 0.73[c]
Segmental MF-BIA	36.46 ± 0.60[a]	23.37 ± 0.63[b]	20.83 ± 0.74[a]	30.21 ± 0.76[b]	38.72 ± 0.77[c]
Difference‖	0.87 ± 0.31[a†]	0.75 ± 0.32[a†]	−1.56 ± 0.38[a‡]	0.58 ± 0.39[b]	3.40 ± 0.39[c‡]
Fat mass (kg)					
DXA	26.19 ± 0.55[a]	20.77 ± 0.57[b]	14.75 ± 0.67[a]	22.54 ± 0.69[b]	33.16 ± 0.69[c]
Segmental MF-BIA	27.66 ± 0.60[a]	22.21 ± 0.62[b]	14.06 ± 0.73[a]	23.49 ± 0.75[b]	37.27 ± 0.76[c]
Difference‖	1.46 ± 0.27[a‡]	1.44 ± 0.27[a‡]	−0.69 ± 0.32[a§]	0.95 ± 0.33[b†]	4.11 ± 0.34[c‡]
Fat-free mass (kg)					
DXA	45.93 ± 0.73[a]	67.55 ± 0.75[b]	52.15 ± 0.89[a]	55.92 ± 0.91[b]	62.16 ± 0.92[c]
Segmental MF-BIA	45.94 ± 0.76[a]	68.11 ± 0.79[b]	54.23 ± 0.93[a]	56.63 ± 0.96[a]	60.22 ± 0.97[b]
Difference‖	0.02 ± 0.26[a]	0.56 ± 0.27[b§]	2.08 ± 0.32[a‡]	0.71 ± 0.33[b§]	−1.94 ± 0.33[c‡]

BMI, body mass index; DXA, dual x-ray absorptiometry; MF-BIA, multiple-frequency bioelectrical impedance analysis

* All values reported as mean ± SE. Means not sharing a common superscript letter are significantly different between genders or between BMI groups ($P < 0.05$).

† $P \leq 0.006$, significantly different from zero.

‡ $P < 0.0001$, significantly different from zero.

§ $P \leq 0.04$, significantly different from zero.

‖ MF-BIA minus DXA.

Among obese women, segmental SF-BIA significantly underestimated body fatness by 5% [12]. The recurrent finding of larger errors in the estimation of %BF with segmental BIA with increasing adiposity is consistent with the findings of the present study. It is noteworthy, however, that none of these studies was designed with power estimates calculated to identify significant differences between the methods.

Other attempts to validate segmental BIA have used various indirect approaches. Among healthy adults, Bedogni et al. [20] derived a regression model, based on the cumulative resistance index at 500 kHz, to predict total body water (TBW) in 35 healthy adults and then cross-validated the prediction model in another 15 adults; they observed the error to be 3 L or 8% of the mean measured TBW. Other investigators performed similar cross-validation trials to ascertain the accuracy of segmental MF-BIA to estimate TBW and extracellular water. Sartorio et al. [26] reported errors of 2.1 L (5%) and 1.3 L (8%) for TBW and extracellular water, respectively, in 38 overweight and obese adults. Medici et al. [27] found that segmental MF-BIA significantly overestimated FFM (4.1 kg) when prediction equations developed in healthy controls were applied to patients with renal disease and receiving peritoneal dialysis. Thus, prediction models, derived and cross-validated in small samples, yield appreciable errors in estimating %BF (2.6–3.2%) and fluid volumes (2–3 L) that limit the use of segmental SF- and MF-BIA for individual predictions of body composition.

It is noteworthy that segmental MF-BIA significantly underestimated and overestimated %BF in adults with N and OW BMI, respectively (Table 2). The biological significance of these errors is small (−1.56% and 0.58%) and are within the precision of the BIA and DXA instruments (2%). Thus, it is uncertain whether the error may be attributed to either technique.

The observed errors of segmental impedance predictions of FFM in the N, OW, and OB groups suggest some general weaknesses of this method. Dependence on proprietary regression equations to estimate conductor volume (e.g., FFM) without evidence of validity and precision is a concern. Lack of information on the sample size, subject characteristics, and the dependent variables, other than resistive index, used to develop and validate the proprietary prediction models hamper the general use of these prediction equations. Use of distal limb detecting electrodes to indirectly estimate truncal resistance also may be problematic. In the development of the segmental resistance model, Organ et al. [8] showed that distal measurement electrode placements significantly overestimated truncal resistance compared with actual measurements of the thorax (23.6 versus 18.3 Ω for men and 30.3 versus 23.8 Ω for women) in supine adults and were only correlated moderately (R^2 = 0.58 to 0.71 for men and women). In contrast, the indirect and direct resistance measurements of the limbs were equivalent by site and highly correlated by limb for the men and women (R^2 = 0.96 to 0.98). In contrast to the original segmental BIA method [8], the present approach relies on distal electrode placements on the hands and feet and provides an indirect estimate of resistance of the trunk. Cornish et al. [28] recognized the problem of unequal current distribution in measuring the impedance of adjoining body segments where cross-sectional areas are very different. They reported that the use of indirect measurements in supine subjects based on hand-to-foot detector electrode placements slightly underestimated impedance values (1%) with a variability (e.g., SD) of 2%, which was considered to be similar to the anticipated change due to intervention. Comparisons of resistance values determined in healthy people in the standing position and using direct and indirect mea-

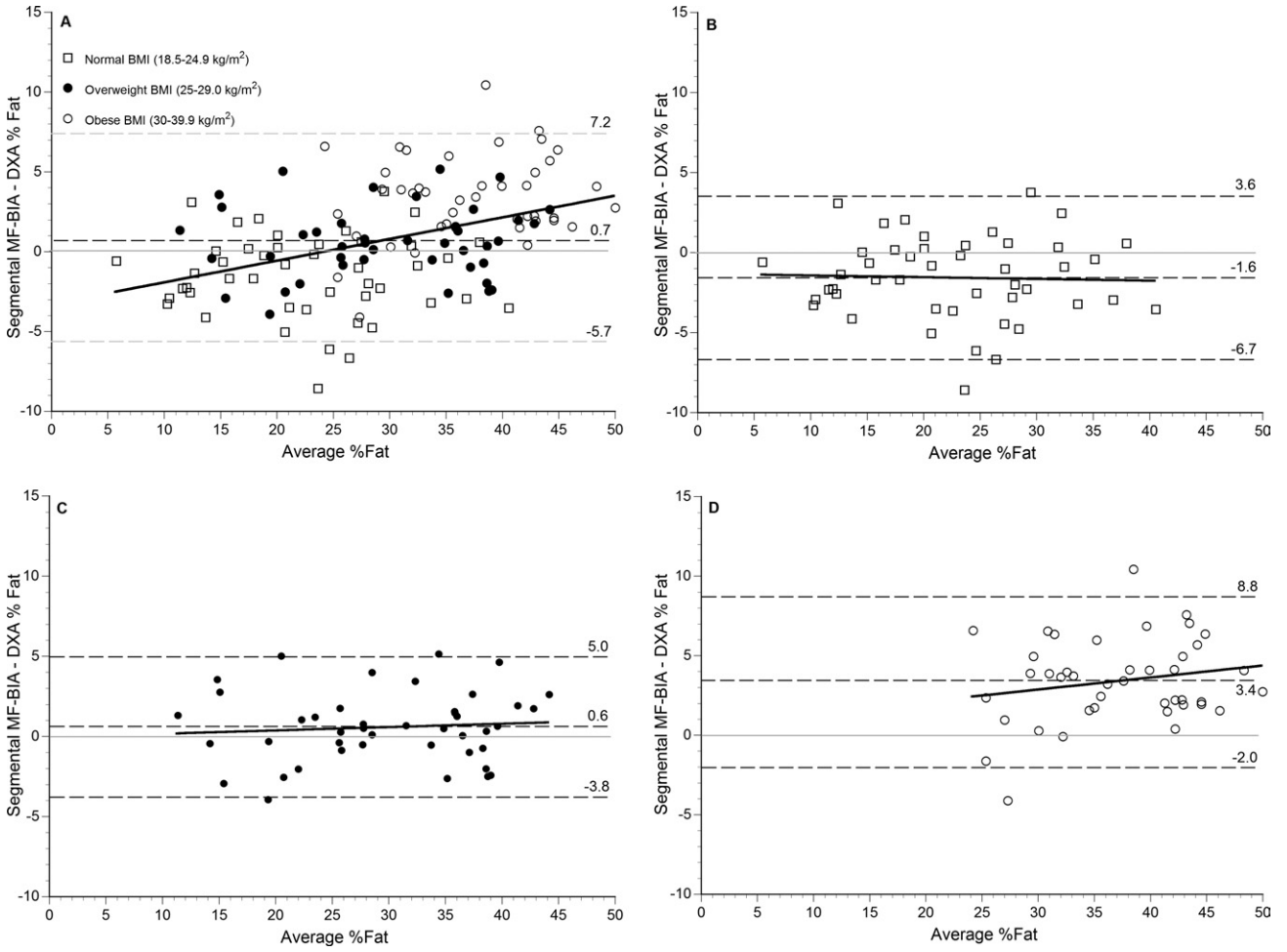

Fig. 1. Discrepancy between % fat determined by using DXA and segmental MF-BIA. Solid line represents the linear relation between mean differences in % fat (%fat = MF-BIA − DXA) and average body fat ([DXA + MF-BIA]/2); dark abbreviated line represents the mean difference; and light abbreviated lines represent the 95% confidence interval. Data are presented for (A) the entire sample ($n = 132$; $R^2 = 0.18$, $P < 0.0001$, RMSE = 2.92), (B) the normal BMI (18–25 kg/m^2) group ($n = 46$; $R^2 = 0.001$, RMSE = 2.61), (C) the overweight BMI (25–29 kg/m^2) group ($n = 44$; $R^2 = 0.01$, $P < 0.05$, RMSE = 2.22), and (D) the obese BMI (30–40 kg/m^2) group ($n = 42$; $R^2 = 0.04$, $P = 0.86$, RMSE = 2.64). BMI, body mass index; DXA, dual x-ray absorptiometry; % fat, percentage of body fat; MF-BIA, multiple-frequency bioelectrical impedance analysis.

surements are not available. Furthermore, the finding that waist circumference explained a significant amount of variance (36%) in the prediction of the error of segmental MF-BIA %BF values (Fig. 2) supports the contention that the present segmental BIA method fails to adequately assess trunk impedance components. Also, differences in body geometry among the BMI groups and perturbations in fluid content and distribution in adipose tissue that affect trunk resistivity of the obese compared with the other BMI groups [27,29,30] have been shown to adversely affect the validity of BIA to estimate body fatness in obese adults. Thus, the reported errors in the prediction of body composition with the segmental MF-BIA devices, particularly in obese individuals, may be the result of a combination of physical factors.

Another concern of some segmental BIA instruments is the use of a limited range of current frequencies that might limit signal penetration into all conductive tissues. Gibson et al. [31] compared estimates of body fatness derived with segmental MF-BIA analyzers that used currents of up to and exceeding 250 kHz. Compared to reference %BF determined with a four-component model, both segmental BIA instruments predicted similar values in men. However, the segmental MF-BIA devices, regardless of range of current frequency, significantly underestimated %BF in women by 2.5-3.0%. Furthermore, the confidence intervals for prediction of body fatness for an individual were very broad (−10 to 10%) for each device. Thus, the use of signal frequencies greater than 250 kHz did not improve the precision of estimation of body fatness with segmental BIA.

A potential limitation of the present work is the use of fan-beam DXA as the reference method to assess body fatness. Although DXA-derived estimates of soft tissue composition are highly correlated with determinations from criterion methods, modest variations in absolute values of compositional variables by DXA have been reported [32].

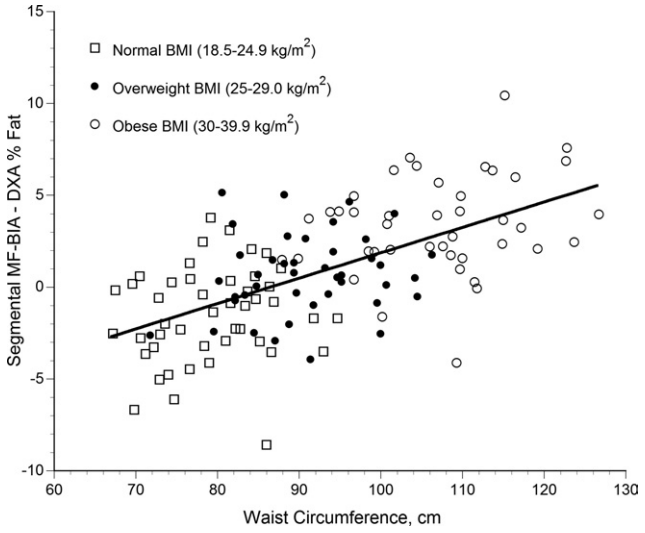

Fig. 2. Waist circumference as a predictor of the error in the estimation of body fatness estimated by using segmental MF-BIA compared with DXA in 132 adults ($R^2 = 0.363$, $P < 0.001$, RMSE = 2.57). BMI, body mass index; DXA, dual x-ray absorptiometry; % fat, percentage of body fat; MF-BIA, multiple-frequency bioelectrical impedance analysis.

Fan-bean compared with pencil-beam DXA has been shown to underestimate %BF 4–7% in subjects with body fat levels exceeding 23% [33]. Attempts to reconcile the errors of fan-beam DXA based on comparisons with reference methods have yielded robust correction factors derived from group data [32,34]. Application of any correction factor should be done with caution because the validity of the factor in different ranges of body size has not been demonstrated.

In conclusion, the findings of this study indicate that segmental MF-BIA significantly overestimated %BF in men and women by less than 1%, which was within the reproducibility of the candidate and reference methods. Among adults classified by BMI as normal and overweight, segmental MF-BIA underestimated %BF within the tolerance of the reference method. However, segmental MF-BIA significantly overestimated body fatness among adults classified as obese. Factors that contribute to errors in assessment of body composition include questionable BIA prediction models and possible inaccurate measurement of resistance in the body torso. Future research efforts should examine the validity of the segmental MF-BIA models to predict body composition in volunteers with diverse body shapes and compositions and in response to changes.

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